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High frequency transducer dedicated to the high-resolution in situ measurement of the distance between two nuclear fuel plates

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Abstract

Most high flux reactors for research purposes have fuel elements composed of plates and not pencils. The measure of inter-plate distance of a fuel element is tricky since a resolution of a micron is searched to measure plate swellings of about ten microns while the dimension between the plates is close to the millimeter. This measure should provide information about the fuel and particularly its history of irradiation. That is the reason why a solution has been considered: a robust device based upon high frequency ultrasonic probes adapted to the high radiation environment and thinned to 1 mm to be inserted into a 1.8 mm width water channel between two fuel plates. To achieve the expected resolution, the system is excited with frequencies up to 150 MHz. Thanks to a specific signal processing, this device allows the distance measurement through an ultrasonic wave's time of flight. The feasibility of such challenging distance measurement has already been proved with success on a full size irradiated fuel element of the RHF.

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1. Introduction

The High Flux Reactor (RHF) of Laue-Langevin Institute (ILL), solely dedicated to research, possesses a core made of a highly enriched Uranium fuel element. It uses heavy water as a moderator in order to slow down the neutrons produced by the fission reaction. This allows the ILL to generate the most intense continuous flux of

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thermal neutrons, about $1.5 \cdot 10^{15}$ neutrons per second per cm^2 , with a thermal power of 58 MW. The core, made of 280 curved fuel plates, is located in a pool of demineralized water allowing a neutron and gamma radiance protection. Paying particular attention to safety and security, the ILL wishes to develop some tools to control the structure modifications of its fuel element. More specifically, the inter-plate distance is a parameter full of information, especially regarding the element irradiation history. This measurement is delicate as a micrometer resolution is desired due to the microscopic structure modifications of plates (swelling of plates, oxide layer...) while the inter-plates distance is close to the millimeter. Furthermore, the access to curved fuel plates inside the water pool is very difficult and all measurement systems are subjected to high radiations.

Based on different methods, distance measurements can be performed by magnetic (Djuric et al., 2009), capacitive (Sakai, 2008), optical (Amann et al., 2001), or other (micro-waves sensor, tunneling sensors...) devices. These can nowadays reach a nanometer resolution, would it be in high-temperature and/or high-pressure environments. However, they can be cumbersome and may not be integrated between plates where space is very limited (optic devices). They may neither meet the requirement of high radiation resistance (magnetic devices) or being immersed with harsh access constraints (capacitive devices).

To address this problem, two specific high frequency ultrasonic transmitters/receivers were first studied, then developed and finally tested on a full size irradiated fuel element of the RHF. Adapted to the high radiation environment, these transducers were designed with nuclear QA (materials, cleanness, dimensional control...) to be inserted into a 1.8 mm width channel between curved fuel plates under water. They were set on a blade leading to a total device thickness of only 1 mm. To achieve the expected resolution, the system is excited with frequencies up to 150 MHz and integrated into a set of high frequency acquisition instruments.

Based on the pulse-echo method, the transducers measure distances from the time of flight (TOF) of the signal reflected by the fuel surfaces (Marioli et al., 1988). The TOF (t) is the interval from the transmission of an ultrasonic pulse to the reception of echoes reflected from the plates. It relates the distance d between fuel plates to the speed of sound c in the medium (water), through the simple equation $d = c \cdot t / 2$.

The developed transducers were then tested with success between fuel plates of High Performance Research Reactor spent fuel elements, proving the feasibility of such challenging measurement. Moreover, it was demonstrated that the different components of the ultrasonic transducers showed good resistance to radiations. Moreover, the quality of the signal to noise ratio was clearly sufficient to obtain a very stable estimation of the inter-plate distance while some flaws may still have to be corrected to perform absolute measurements.

2. Materials and methods

2.1. The operating mode

To study the behavior of fuel elements after irradiation, a device able to measure the width of the water channel existing inside the reactor core was designed. It will allow the characterization of the plate swelling, inherent to consumption.

In more details, the designed device is a waterproof dual transducer emitter/receiver mounted on a stainless steel blade. It was designed to be moved inside the water channels having a nominal thinness of 1.8 mm. Each transceiver measures the distance between its own surface and the facing plate. Knowing the speed of sound in water and the thickness of the blade, the total distance between the plates can be obtained by the determination of the TOF (t) existing between an emitted ultrasonic pulse and the reflected echoes from each plate. The inter-plate distance can be estimated by the formula:

$$d_{\text{inter-plate}} = d_{\text{blade}} + c \cdot t / 2 \quad (1)$$

Where c is the propagation velocity of the signal in water which is temperature dependent.

2.2. Mechanical holder: blade and support

The ultrasonic transducers were mounted on one end of a stainless steel blade with the following dimensions: a thickness of 1 mm, a width of 16 mm and a length of 620 mm. To set up the cables a groove was made on both faces of the blade. This latter is then connected to a support (a 22 mm diameter and 4 m long tube divided into two parts) moved from above at a distance corresponding to the depth of the fuel element in water. The connection is made possible thanks to screws positionned on the blade side and thanks to a thread on the pole side (see figure 2).

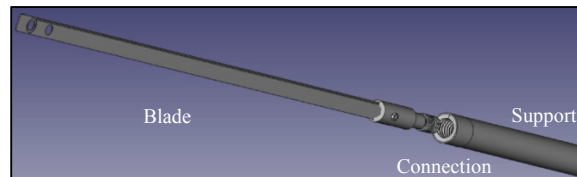


Fig. 2. Connection of the sensor to the support

2.3. Transduction elements

Both transducers possess the same multilayered structures composed of piezoelectric elements welded on one surface to a gold electrode (figure 3). An aluminum layer is deposited on the second surface as an electric input and output electrode. A thin glue layer welds the whole system to a delay line of silica. Transducers have been chosen to have a frequency bandwidth extending beyond 150 MHz. At these high frequencies, the structure of the multilayered sensor plays a central role in the shape of transmitted and received signals. In fact, when an electrical pulse excites the piezoelectric element, the ultrasonic wave propagates through the layers, producing series of acoustic echoes. Multiple reflections occur in the silica delay line leading to echoes reflected to the sensor and to series of complementary transmitted signals in water. The successive reflections of the latter in the water layer between the silica and the plate interface then lead to series of signals with decreasing amplitudes (see figure 4).

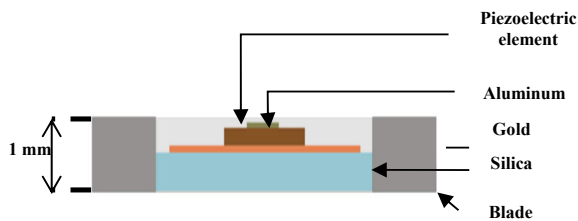


Fig. 3. Ultrasonic transducer

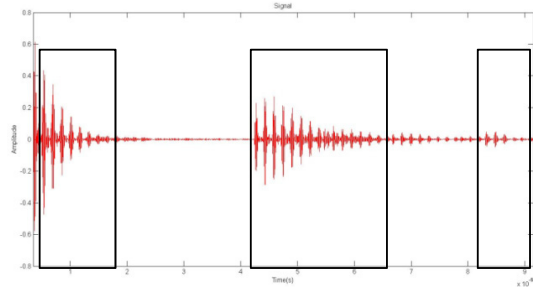


Fig. 4. Signals collected by an ultrasonic transducer

3. Experimental results

To study the behavior of the fuel elements after irradiation, an in-situ experiment leading to a first measurement of the inter-plate distance within a fuel element of the RHF reactor was performed. The fuel element was placed 4 meters under water. Distance measurements were made with the designed blade handled by an operator with a 5m long stainless steel support. Measures have been performed in the upper central portion of the element in two positions one of which is shown in Figure 5. Results of the first experiment of distance measurement are presented in the graph of Figure 6.

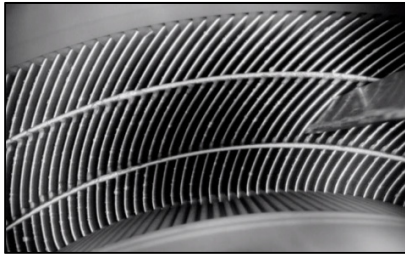


Fig. 5. Positioning of the blade between two fuel plates

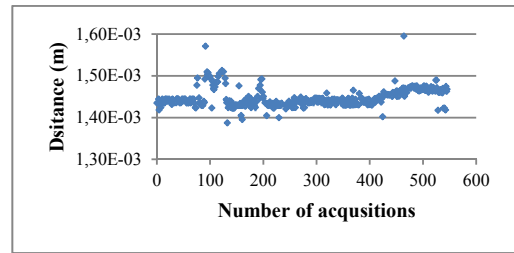


Fig. 6. Experimental results

These results clearly show that despite the highly radiative nature of the environment the quality of the ultrasonic signals was sufficient to ensure a stable identification of the inter-plate distances. Several observations can be made from Figure 6. For the first 400 acquisitions, the distance is equal to $1,44 \pm 0.005$ mm with a high stability. The difference between this value and the initially expected 1.8 mm can be explained by geometric problems such as non-parallelism of transducers relative to plates. The influence of the temperature or the nature of the water on the acoustic velocity should also be taken into account. Finally, measurements were performed at the ends of the fuel plates where they may be slightly curved. The large variations observable between the 80th and the 120th acquisition as well as around the 200th correspond to withdrawals of the sensors from the measurement areas and should not be considered as relevant. A slight increase of the distance (1.47 ± 0.001 mm) can be observed beyond acquisition 400 indicating a change in the thickness of the water channel.

4. Conclusion

This paper presents a specific device using two high frequency ultrasonic sensors, radiation resistant, allowing the measure of fuel plates' swelling inducing water channel thickness variations inside a High Flux Reactor. It contains two ultrasonic transducers inserted at the end of a blade. With a total thickness of 1 mm, the device is further attached to a cylindrical holder to be manipulated from a distance of the order of 5 meters below the water surface. To allow a precise monitoring of the fuel element evolution, a resolution of a micron is searched while the dimension between the plates is close to the millimeter. To achieve this expected resolution, the system is excited with frequencies up to 150 MHz and integrated into a set of high frequency acquisition instruments. Knowing the speed of sound in water, the device allows the distance measurement through the evaluation of the ultrasonic wave's time of flight. The feasibility of such a challenging measurement in a highly radiative environment has then been proved and the experimental constraints have been identified. They will be considered in future works to improve the measurement reliability. In particular, the temperature dependence of the measure is presented in a second paper.

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